# Beam Dynamics and Commissioning

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## Overview and recent RHIC design developments

Introduction: machine parameters, operating scenarios, and lifetime issues.

Correction systems: single layer and four layer correctors in the arcs and in the Interaction Regions.

## Active beam dynamics issues

Magnetic field quality control: expected harmonics, contractual harmonics, and as-built harmonics.

Longitudinal manipulations: emittance preservation during passage through transition and re-bucketing.

Instabilities and impedances: impedance budget and feedback systems.

Flexibility: Species, IR optics in the collider, matching in the transfer lines.

## Commissioning - the sextant test

Physics goals: beam and optics measurements.  Cf LEP octant test.

Controls goals: hardware and software.

Databases: information integration.

## Conclusions

Beam dynamics design is complete, bar routine maintenance and investigation of performance limitations.

Strong new emphasis: commission the sextant as fully as possible

# Lattice RHIC92 version 0.3

<u>Several minor modifications</u> have been made in the last 12 months, reflected in the RHIC92.0.3 optics database, and in the Design Manual:

split integer working point: $Q_h, Q_v$ = 28.19, 29.18
phase advance between low beta IP's: $\Delta Q_h, \Delta Q_v$ = 5.238, 4.247
first order matched transition jump
relocated octupole/decapole correctors
refined triplet quadrupole correction strategy

<u>8 cm correctors</u> are either 1 layer (dipole) or 4 layer

| | | |
|---|---|---|
| dipole layers: | normal or skew | closed orbit, H and V |
| quad layer: | normal or skew | transition jump, linear decoupling |
| octupole layer: | normal | quadratic chromaticity |
| decapole layer | normal | not connected - contingency |

<u>13 cm correctors</u> in IR quad triplets are 4 layer, and fit in with a detailed correction strategy

field quality measurements are made on every IR quad, prior to individual (quadrupole) and group (triplet) dead-reckoned correction.

$\beta_{max} \approx 1400$ meters in low beta quads (because of D0 and DX dipoles between the interaction point and Q1).

after 10 hours of gold storage, $\varepsilon_N = 40 \, \pi$ mm mrad, and the $5\sigma$ beam size is 71% of the 6.5 cm coil radius.

all IR's have identical IR optics layout, but different correction layer connections according to nature of each IP.

triplets lie side-by-side in Yellow and Blue rings, with a common cryostat for Q1 magnets.

# Triplet correction strategy

Nominal operating tunes, 29.18 and 28.19, lie between 5th and 6th order
resonances - tune spread must be << 0.033..

Design dispersion is small - chromatic tune spread is dominated by
chromaticity (2 x 2.5 x 0.0009 = 0.0045)

First, the integrated harmonics of individual quads are measured, and then
trimmed to zero using "tuning shims"

Second, body and end measurements from 3 quads and 1 D0 dipole are used to
set triplet corrector settings to minimize tune spread

Local correction is necessary because $\beta$ varies rapidly in the triplet

In the table below, "S" implies shimming, and "C1", et cetera, implies
excitation of a corrector winding

| ORDER, n | NORMAL, $b_n$ | SKEW, $a_n$ |
|----------|---------------|-------------|
| 0 | C1 or C3 | C3 or C1 |
| 1 | - | C2 |
| 2 | S, (C2) | S |
| 3 | S, C1, C3 | S, (C2) |
| 4 | S, C1, C3 | S |
| 5 | S, C1, C3 | S, (C2) |
| 6+ | - | - |

Tune spread before correction is unacceptable: tune spread after correction is
less than that due to linear chromaticity

Performance predicted by simple perturbation theory is consistent with results
from complex long time tracking

# Magnetic field quality control

Arc dipoles and quadrupoles are being built in industry, with first assembly in February '94. First production run of 30 will be used in the sextant test.

IR quads, correctors, DX and D0 dipoles, et cetera, are being built at BNL. Assembly of CQS packages is performed at BNL.

BNL has extensive experience in the construction and measurement of multiple prototypes of all magnets critical to beam dynamics performance. Expected harmonics based on these measurements are passed to RHIC Accelerator Physics for evaluation, and updated as design iterations occur.

Rule of thumb: systematic errors are more important than randoms, due to consistent superconducting cable dimensions. Hence, expected harmonics also include expected variation of systematics, for example due to plant tooling particulars.

Field harmonic specifications and mechanical tolerances are written into the industrial contracts. Experience shows that tight control of coil tolerances leads to good field harmonics.

Accelerator Physics will concentrate in future on rapid evaluation of as-built harmonics, as the data come in, via the Magnet Division. This will rely on perturbation analysis (fast) and tracking (not so fast).

More magnet details on Wednesday morning, including harmonic data presented by Peter Wanderer.

# Longitudinal manipulations: emittance preservation

Sequence of manipulations, and their effect on the emittance budget:

Inject box car fashion into 26 MHz "acceleration" system buckets. The AGS injector is required to provide a nominal emittance of 0.2 eV-sec for Au ions, in order to achieve the emittance budget. Some Au bunches will grow by about 20% due to IBS during the 60 second worst case time that they are stored at injection energy.

Accelerate to top energy in about 55 seconds, at 83 A/s.

Cross transition (except for protons) early in the acceleration. RHIC will be the first superconducting collider to cross transition. Transition is a bottle neck for Au, according to standard simulations, with a nominal minimum emittance of about 0.3 eV-sec after passage

Re-bucket from acceleration system to "storage" system (196 MHz). Turn off(on) acceleration(storage) system Allow beam to filament about unstable fixed points of the storage buckets. Snap the RF phase.so that bunch ends up at stable fixed points. Efficient rebucketing requires an emittance of less than 0.4 eV-sec

Store for 10 hours. Intra Beam Scattering and RF noise cause significant leakage of Au ions from storage buckets. Periodically scrape the coasting beam, if experimental background gets too high.

Nominal RF parameters are undergoing modest final optimizations.

Tolerance to noise is being investigated. Noise levels achieved at the SPS appear to be acceptable, even near the separatrix.

More detailed transition crossing simulations are being made.

The significance of IBS coupling strength is being investigated.

For more information, see "The Conceptual Design of the RHIC RF System", May '93, as reviewed by the Machine Advisory Committee.

# Instabilities and impedances

Instabilities

Microwave instability: proton beams have the highest intensity, and are the most vulnerable, with a threshold $Z/n$ of about 10 Ohms at 250 GeV.

Longitudinal couple bunch instability: calculation of thresholds and growth rates show that gold and proton beams appear to be Landau damped and stable in storage.

The longitudinal damper also used to damp injection oscillations will be able to handle longitudinal coupled bunch modes growth rates as high as $10 \text{ s}^{-1}$.

Transverse mode effects are under study, but are not expected to be important.

Impedances

Unshielded bellows would account for about half of the broad band impedance, according to calculations of the impedance budget. Consequently they will be shielded, bringing the $Z/n$ down from about $-2 \text{ i}\Omega$ to about $-1 \text{ i}\Omega$ .

Bench measurements of bellows impedances are in "reasonable" (20%) agreement with calculation.

Narrow band longitudinal coupled bunch modes in the RF cavities are reduced by higher order mode damping to less than $2 \text{ s}^{-1}$ - before Landau damping, and assuming worst case overlap.

"Impedance working group" includes participants from Accelerator Physics, RF, and Instrumentation sections.

# Flexibility

Species

The most awkward pair of species, Gold on protons, has a rigidity ratio of about 2.5, leading to variable trajectories in shared DX splitting dipole.

RHIC92.0.3 incorporates a "hinged" DX magnet, 20 cm coil ID, currently under design. Even with identical species, the beam passes off-center, exploring field nonlinearities.

RHIC optics

Linear optics in six IR's and six arcs are tuned (almost) independently of one another, to give $\beta^* = 1$ to 10 meters, and $\Delta Q$ of approximately 1 unit, along and perpendicular to the diagonal.

Smooth interpolation between "stepping stones" in a ramp (eg low beta squeeze) must be assured within achievable bounds of parameter space, using function generators responding to the Real Time Data Link, RTDL.

In one proposal the 720 Hz RTDL would carry 20 or 30 key parameters, such as $K_F$, $K_D$, $S_F$, $S_D$, skew quad family strengths ..., to achieve knob-like performance.

Transfer line optics

Transfer line takes beam from the AGS, with as yet unconfirmed distribution characteristics, to either the Blue or Yellow ring. Beam/optics matching in or out of all 3 rings must be flexible and diagnosable over a wide range.

Simulations - simple or sophisticated - may be trivially interchanged with reality if the processes have clean data interfaces, and are "sequenced". Low overhead is essential - simulations must teach, not divert.

# Sextant test physics goals

The LEP octant test experience is instructive:

Discovered the dipole bus had to be set 1% or 2% away from its expected value.  This proved, much later, to be an injector (SPS) miscalibration.

Beam then ran to the beam stop with little or no steering.

Extensive experiments showed that the phase advance per cell was off by 1 or 2 degrees, due to a systematic quadrupole transfer function error.

Conclude: there will be much to learn from accelerator physics experiments on the sextant, if the experiments are properly planned, with adequate control system and instrumentation support.

Beam distribution experiment

Measurements on AGS fixed target beams have only qualitatively confirmed that the dimensions of the 6-D "hyperfootball" are as expected.  Adjustment of front end transfer line optics depends on accurate beam measurements.

Beam profiles are digitized in 2-D by CCD cameras looking at 'destructive' profile monitors.  Data from a pair of profile monitors can be deconvolved for non-pathological locations, without scanning intervening optics.

Independent control of the momentum spread, for example by a high dispersion slit, should confirm that the momentum size is relatively small.

Beam optics experiment

Optical transfer functions - matrices - can be measured by observing the response of the beam centroid on downstream Beam Position Monitors, as upstream dipole correctors are perturbed.  This is essentially the LEP cell phase advance experiment.

A necessary pre-requisite is a "beam threading" application program that can steer beam down to the beam stop, and that can confirm the absence of unusual losses on Beam Loss Monitors.

# Sextant test controls goals

Despite the success of the octant test, the LEP control system became notorious for its slow response during storage ring commissioning.

This was partly due to labyrinthine networks - a feature that RHIC will not have - and partly to lack of system integration. The implicit controls paradigm emphasized testing single accelerator devices, albeit remotely.

The most basic aspect of the sextant test - hardware commissioning - fits this paradigm. Getting beam to the end of the sextant requires a significant amount of high level integration, and the accelerator physics experiments outlined above require even more.

RHIC will benefit most from a fully functional control system on day one - when storage is commissioned in '98. Therefore the control system needs to be exercised as fully as possible in '95.

For example, an energy ramp in the sextant does not make sense to the single pass beam, and is an excessive way to test that the power supplies can put out 5,000 Amps without a magnet quench, but it is still a crucial exercise.

# Databases: information integration

BNL has selected Sybase as its standard relational DataBase Management System (rDBMS). Various sections of the RHIC project are building and filling Sybase databases to fit their own needs.

RHIC collider and transfer line design optics are maintained in "ideal optics" databases by the Accelerator Physics section, who are also developing "engineering optics" and other databases.

Controls and Accelerator Physics sections are collaborating on the development of a "configuration" database, for controls routing.

Also in use or in construction are a survey database, an installation database, a wiring database, and an engineering drawing database. More database types will come with the passage of time.

If the design, construction, and maintenance of these databases is properly coordinated, the "relations" between different data sets will enable the powerful integration of information.

Success requires a balance between the autonomous ownership of databases by RHIC sections, and cooperative design of the key features of the tables within each database.

# CONCLUSIONS

1  Performance of the RHIC92.0.3 lattice has undergone 2 successful technical
   Machine Advisory Committee reviews in the last year.

2  Recent minor modifications include split integer nominal tunes, a linear
   transition jump, hinged DX magnets, reorganized corrector layout, and a
   revised IR quad field quality correction strategy.

3  Now that the basic design is complete and stable, we are honing our
   understanding of RHIC ultimate performance limitations.  The limitations
   under study include the preservation of longitudinal emittance, Intra Beam
   Scattering, magnetic field quality, transition crossing, IR correction
   strategies, and the refill time.

4  Coherent instabilities are not expected to be a problem  Their study continues
   and the impedance budget remains controlled.  The broadband impedance
   is halved by shielding the bellows.

5  We eagerly await the industrially built arc dipoles and quadrupoles, scheduled
   for early next year, and continue to improve our evaluation techniques.

6  Commissioning work focuses on the sextant test of '95, when beam will be
   passed from the AGS, through the transfer line and across one arcs worth
   of cells.

7  Experiments on beam quality and optical transfer functions are physics goals
   for the sextant test that naturally stress a high level of system integration.

8  The even higher level controls functionalities required for '98 storage
   commissioning will be exercised in the sextant test, wherever possible.